Introduction to IAEA Safeguards

Applied Antineutrino Physics workshop
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IAEA Safeguards Introduction Topics

- Basic concepts of IAEA Safeguards

- LWR Safeguards

- Issues in LWR Safeguards

- Needs in LWR Safeguards
  - Opportunities for Anti-Neutrino Detector and other new concepts

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In the Beginning: Pre-NPT-
The Agency's Safeguards System (1961-1968)

- The first system
  - The Agency's Safeguards System (1961)
  - INFCIRC/26

- The 1961 system as extended to cover large reactor facilities
  - The Agency's Safeguards System (1961, as Extended in 1964)
  - INFCIRC/26 and INFCIRC/26/Add.1

- The revised system
  - The Agency's Safeguards System (1965)
  - INFCIRC/66

- The revised system with additional provisions for reprocessing plants
  - The Agency's Safeguards System (1965 as Provisionally Extended in 1966)
  - INFCIRC/66/Rev.1

- The revised system with further additional provisions for safeguarded nuclear material in conversion plants and fabrication plants
  - The Agency's Safeguards System (1965, as Provisionally Extended in 1966 and 1968)
  - INFCIRC/66/Rev.2

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Definition of Safeguards - INFCIRC 66

- INFCIRC/66 - limited agreement

- Only Israel, India, Pakistan have this agreement in place

- Technical Aim - "...that special fissionable and other materials, services, equipment, facilities and information are made available by the Agency……and **are not used** in such a way as to **further any military purpose**."

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Treaty on Non-Proliferation of Nuclear Weapons (NPT)

- INFCIRC/66 agreements / Limited Agreements precede NPT (1961-68)

- Negotiations Concluded in 1968

- Entered into Force in 1970

- INFCIRC/153 (corr) agreements
    - Comprehensive Safeguards Agreement (CSA) (June 1972)

- INFCIRC/540 Model Additional Protocol (Sept 1997)
    - Strengthened Safeguards System – Post Iraq War (1991)

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Definition of Safeguards - INFCIRC 153 (CORR)

- INFCIRC 153(corrected) - full scope safeguards

- Technical Aim - "...the **timely** detection of diversion of **significant quantities** of **nuclear material**..."

- Safeguards under 153 known as:
  - Full Scope Safeguards
  - Comprehensive Safeguards Agreement

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Definition of Safeguards - INFCIRC 540 (CORR) - Additional Protocol

- Additional Protocol Provides for more access and information to the IAEA

- For LWR Safeguards – key points
  - IAEA can access auxiliary buildings on site
  - Integrated Safeguards
    - Because of "Broader Conclusion" can reduce some SG effort

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Basic Types of IAEA Inspections

- # Physical Inventory Verification – PIV
  - **1** x year at LWR

- # Design Information Verification – DIV
  - **1** x year at LWR with PIV

- # Interim Inspections
  - For timeliness - 4 x year at LWRs (for CF and SF)
  - For verification of domestic and international transfers

- # Additional Protocol – INFCIRC 540
  - Complementary Access (CA) Activities

- # Special Inspections – INFCIRC 153

"Timeliness" - Material Guidelines

Nuclear Material	Material Form	Conversion Time
Pu, HEU or U-233	Metal	few days (7-10)
Pure Pu components	Oxide (PuO_2)	few weeks (1-3)
Pure HEU or U-233 compounds	Oxide (UO_2)	few weeks (1-3)
MOX	Non-irradiated fresh fuel	few weeks (1-3)
Pu, HEU or U-233	In scrap	few weeks (1-3)
Pu, HEU or U-233	In irradiated fuel	few months (1-3)
LEU and Th	Unirradiated Fresh Fuel	order of 1 year

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"Significant Quantity" - Defined

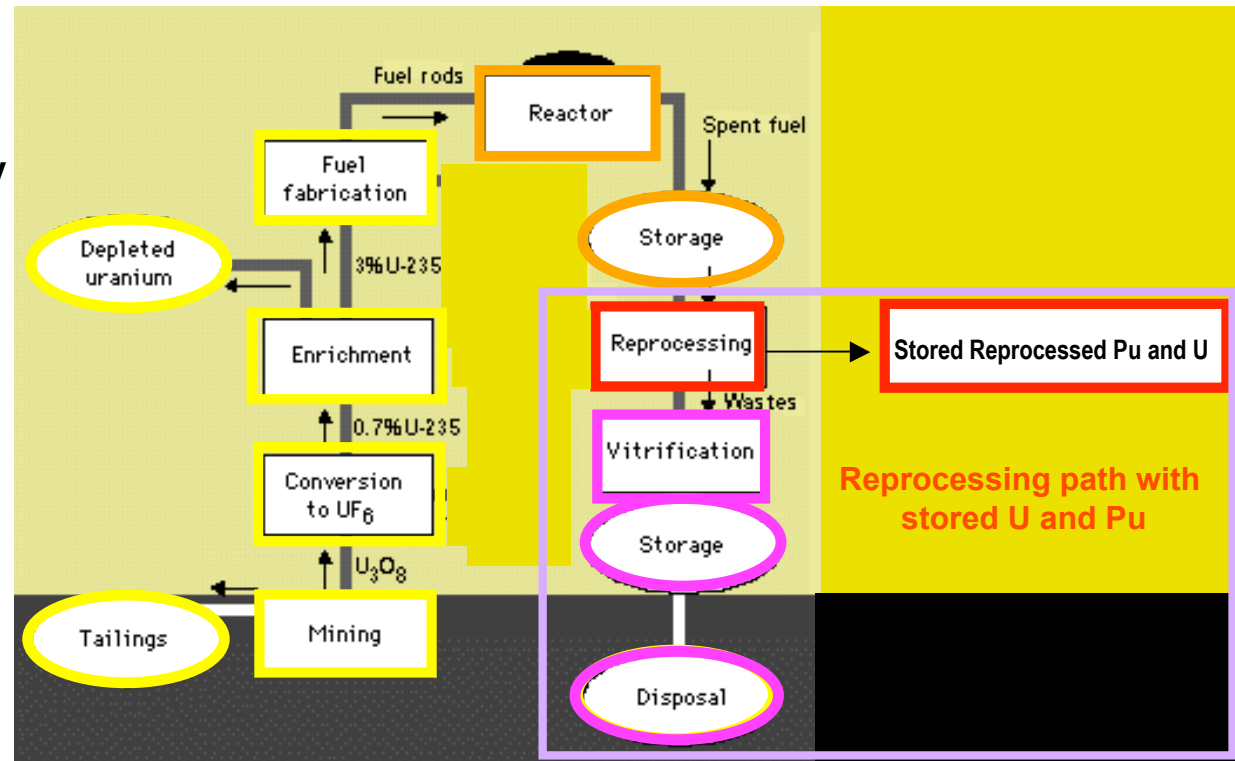| Nuclear Material	SQ in KG
Pu (<20% Pu-238)	8 kg Pu
U-233	8 kg U-233
HEU (=>20% U-235)	25 kg U-235
LEU (<20% U-235 including natural U and depleted U)	75 kg U-235 (or 10 t nat. U or 20 t depleted U)
Thorium	20 t thorium

Timeliness Goal

MATERIAL CATEGORY	EXAMPLES	TIMELINESS GOAL
Unirradiated Direct -Use	HEU fresh fuel, MOX	1 MONTH
Irradiated Direct -Use	Spent fuel, core fuel	3 MONTHS
Indirect -Use	LEU Fresh fuel	1 YEAR

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LWR Safeguards – Fuel Cycle Relevance
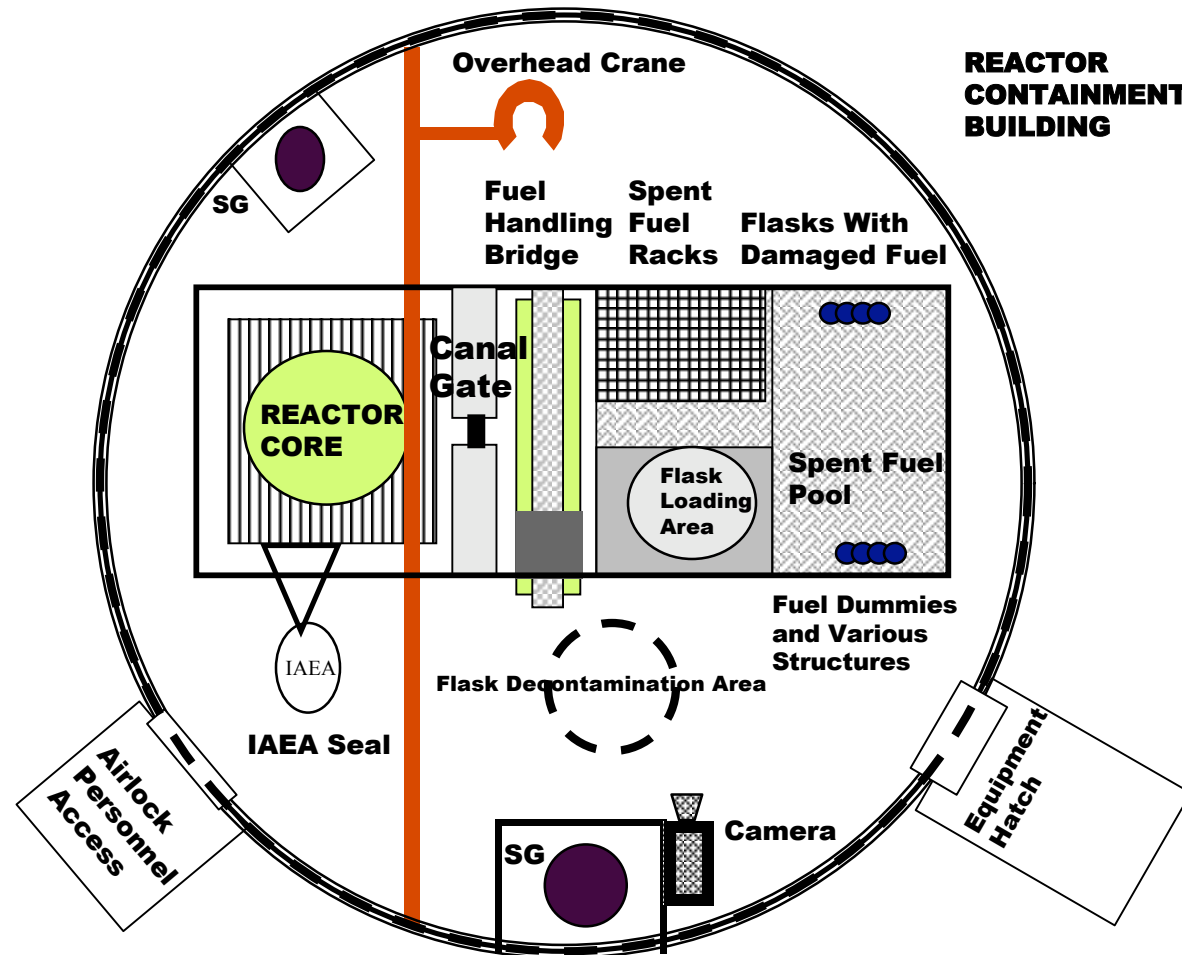
Nuclear Material Color Key
Yellow – Indirect Use
Orange – Irradiated Direct Use
Red – Unirradiated Direct Use
Pink – Waste
        + No U or Pu
        + OR SGs terminated

Fuel rods

Reactor

Spent fuel

Fuel fabrication

Depleted uranium

Storage

3%U-235

Enrichment

Reprocessing

Stored Reprocessed Pu and U

0.7%U-235

Wastes

Vitrification

Conversion to UF$_6$

Reprocessing path with stored U and Pu

U$_3$O$_8$

Storage

Tailings

Mining

Disposal

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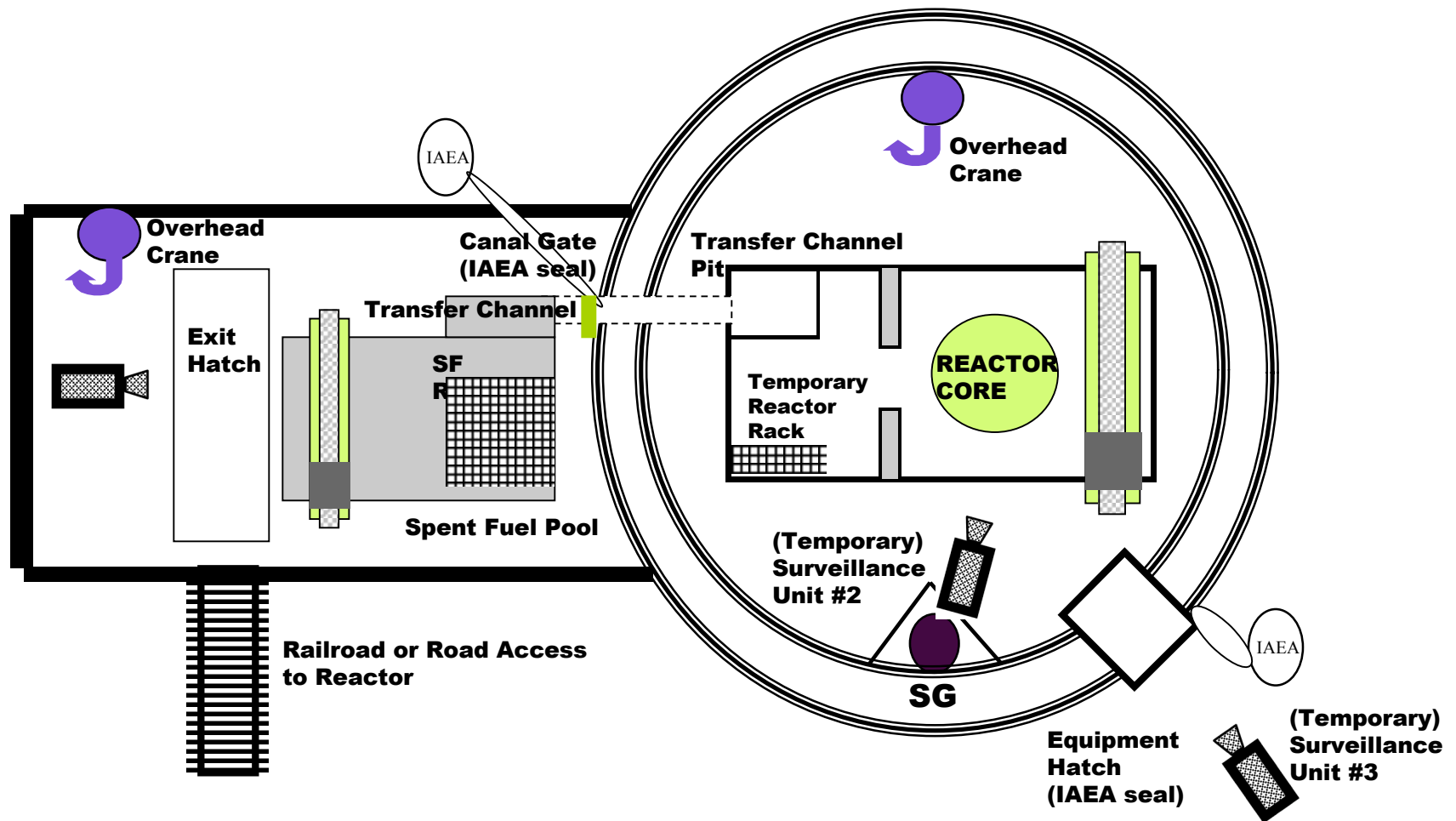The World's Greatest Science Protecting America

LWR Categories

- **Type 1 - Reactor hall includes spent fuel pool**
  - VVER 440 (Loviisa 1-2, Paks 1-4, Bohunice 1-4, Rovno 1-2)
  - VVER 1000 (Kozloduy 5-6, Temelin 1-2, Khmelnitsky 1, Rovno 3)
  - BWRs with SF pool in containment (TVO-1, TVO-2)
  - PWRs with SF pool in containment (*Biblis 1-2*)

- **Type 2 - Spent fuel pool outside of reactor hall**
  - PWRs with SF pool in separate building (Krško, Almaraz 1-2)
  - BWRs with SF pool in separate building (*Liebstadt*)

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LWR Layout - Type I Reactor Design

REACTOR
CONTAINMENT
BUILDING

Overhead Crane

Fuel
Handling
Bridge

Spent
Fuel
Racks

Flasks With
Damaged Fuel

SG

Canal
Gate

REACTOR
CORE

Flask
Loading
Area

Spent Fuel
Pool

IAEA

IAEA Seal

Fuel Dummies
and Various
Structures

Flask Decontamination Area

Airlock Personnel Access

Equipment Hatch

SG

Camera

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LWR Layout - Type II Reactor Design

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Examination of records and reports - Accountancy Side of IAEA Safeguards

- **Nuclear Material Accountancy - Terms**
  - PIV = physical inventory verification
  - PIL = physical inventory listing
  - LII = list of inventory items
  - MBR = material balance report
  - ICR = inventory change report
- **Check the movements of nuclear material**
  - Receipts
  - Shipments
  - Transformation - calculate nuclear loss (U) and production (Pu)
- **Reactors – LWR, OLRs (On Load Reactors), Fast Reactors**
  - Item Facilities – all nuclear material in unit form (Fuel Assemblies)
  - No Material Unaccounted For (MUF) expected
  - Shipper/receiver difference (SRD) from SF sent to reprocessing
    - **Uncertainties on U and Pu inventories**
      - **Operator calculations**
      - **Reprocessing plant measurements**

Physical inventory verification (PIV)

- PIV – yearly - the period between PIVs not to exceed 14 months
  - Performed when core is refueled or opened
  - If core not refueled or opened - PIV done with closed core
  - Multiple cores (VVER 440 - twin reactor per facility)
    - Do PIV during *one* of the core openings
  - Post PIV period does not exceed 3 months

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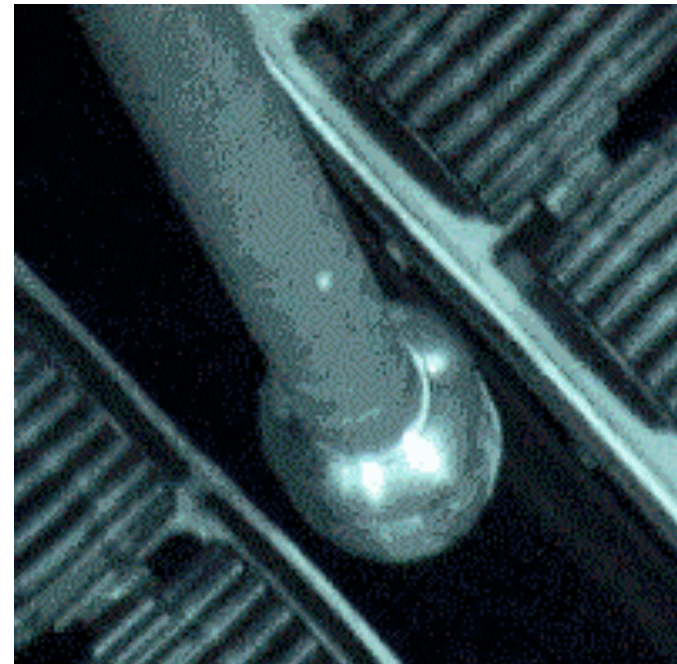
PIV - Fresh Fuel Verification

- FF assemblies and separate fuel pins are:
  - *Item counted*
  - Verified for *gross defects* <u>or</u> by *serial number ID (by random sampling)*

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MMCC - Portable Multi-channel Analyser + CdTe Detector

- ## MMCC Detects 186 keV U-235 γ peak in γ spectrum

  - CdTe detector
    - ➢ inserted into fuel assembly
    - ➢ gamma spectrum measured
  - Definitive gross defect measurement of
    - ➢ Fresh LEU fuel
    - ➢ U-235 **is** or **is not** present

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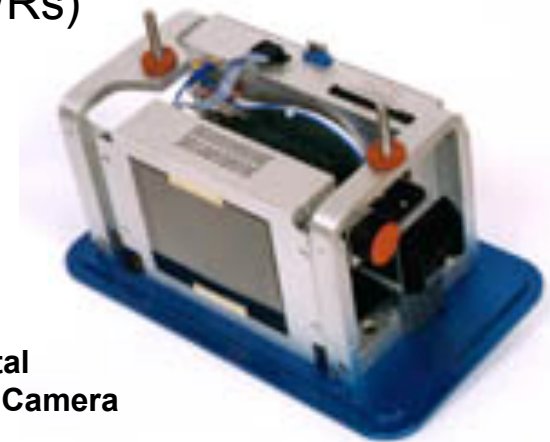# PIV - Core Fuel Verification

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- **Open core** –
  - —Assemblies *item counted* and
  - —*Acceptable C/S maintained* either on
    - ➤ Open core or on removal routes
- **Discharged core** - core is discharged to SF Pool
  - —Verify along with SF
  - — *Acceptable C/S maintained* either on
    - ➤ Open core <u>or</u> on removal routes
- **Closed cores**
  - — If under C/S - the C/S system is evaluated

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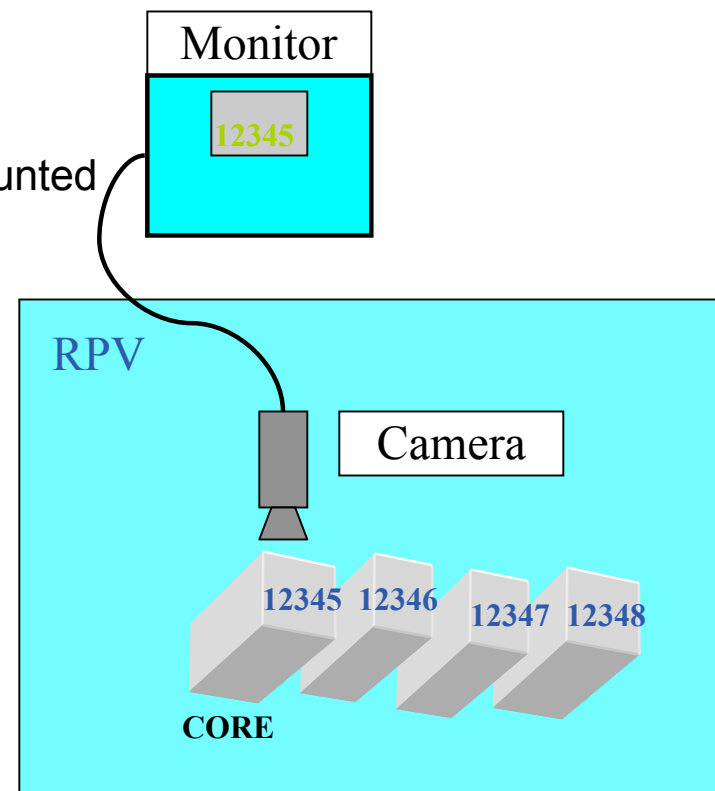
Surveillance

- ## Surveillance Used in LWRs

  - Reactor Hall
    - ➤ Core Fuel During Refueling: Type 2 LWR
    - ➤ Core Fuel / Spent Fuel / Casks Core Fuel: Type 1 LWR
  - Separate SF Pool
    - ➤ Spent Fuel Pool and/or Exit Routes
  - Exits (Large enough to move SF cask through)
    - ➤ Containment Hatch (Westinghouse PWRs)
    - ➤ Containment Hatch (VVER 1000)
    - ➤ Loading Bay in SF Pool (Type 2 LWR)

**DCM-14 Digital
Surveillance Camera**

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UWTV - Underwater TV

- ## UWTV used to verify Core Fuel during refueling

  - The TV camera pans across the fuel
    - ➢ Serial numbers are verified
    - ➢ The total number of fuel assemblies counted
    - ➢ Compared to the operator's declaration

Monitor

12345

RPV

Camera

12345 12346 12347 12348

CORE

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PIV - Spent Fuel Verification... In practice

- ## SF Pools verified 100% for Gross Defects
  - Easier to verify all items then to select specific items in pool
  - ICVD - SF and SF Pool conditions determine success of method

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    - ➢ Water quality

    - ➢ Fuel assembly burn-up

    - ➢ Residence time in pool by SF

  - With failure of ICVD
    - ➢ Use of SFAT or similar method is attempted
  - IAEA has new intense interest in NON-FUEL items in SF pool
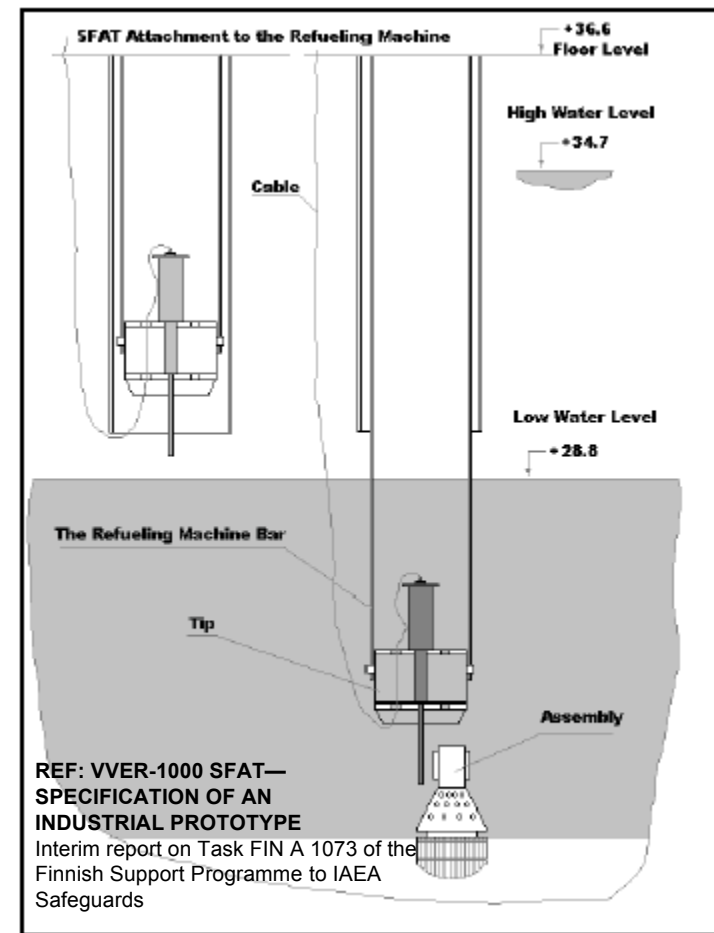
ICVD - Improved Cerenkov Viewing Device

- ## ICVD Detects Cerenkov Glow From SF and Verifies

    – Spent Fuel
      - ➢ Spent Fuel Pools
      - ➢ Spent Fuel in…
        - ▪ Baskets and/or
        - ▪ Casks prior to shipment
    – Core Fuel
      - ➢ Core Fuel during refueling
        - ▪ To recover from *anomaly*
      - ➢ EXAMPLE: Loss of "CofK" of Core
        - ▪ Recovered next PIV during refueling

Sweden - CLAB

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SFAT - Spent Fuel Attribute Tester
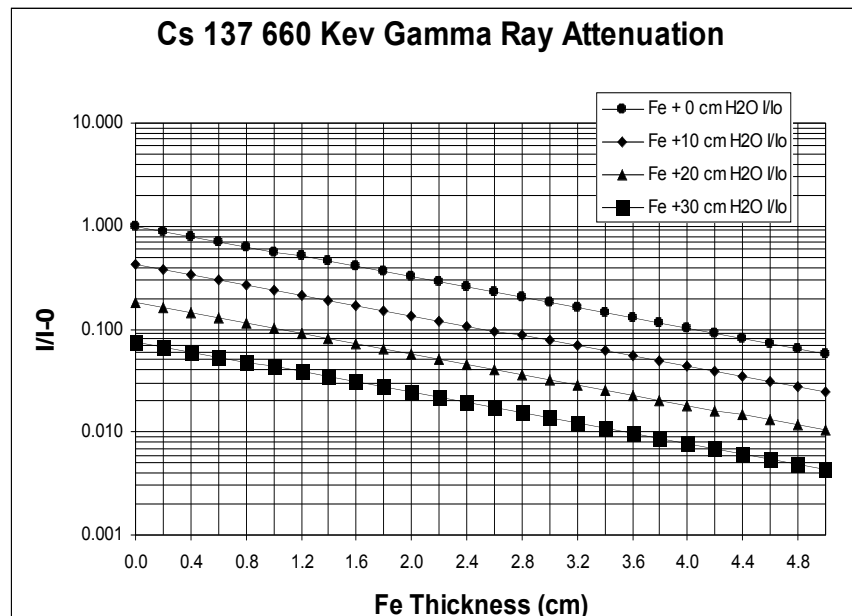
• SFAT Properties

- Detects
  - ➤ Cs-137 660 keV gamma peak
  - ➤ Characteristic of fission products
- Used to verify
  - ➤ SF Pool fuel – ICVD not usable
    - ▪ Too old - Radiation decaying away
    - ▪ Fuel with low burn-up – Too few FPs
  - ➤ SF Pool *items* that may be
    - ▪ Dummy elements
    - ▪ Skeleton assemblies
    - ▪ Empty containers
  - ➤ ID by lack of a Cs-137 peak

REF: VVER-1000 SFAT—
SPECIFICATION OF AN
INDUSTRIAL PROTOTYPE
Interim report on Task FIN A 1073 of the
Finnish Support Programme to IAEA
Safeguards

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SFAT Issues
Attenuation of γ Source in SF Pool by Castor Material and H₂O

$$I = I_o\, e^{-(\mu_{H2O} x_{H2O} + \mu_{Fe} x_{Fe})}$$

- Castors with iron
  - Attenuates gammas

- Water covering SF in castor
  - Attenuates gammas

- If SFAT not close enough to SF
  - **Inspector SFAT NDA of damaged SF castor**
    - **Difficult to distinguish between…**
      - **Empty irradiated castor**
      - **Castor containing SF**

Cs 137 660 Kev Gamma Ray Attenuation

Legend:
- Fe + 0 cm H2O I/Io
- Fe +10 cm H2O I/Io
- Fe +20 cm H2O I/Io
- Fe +30 cm H2O I/Io

Y-axis: I/I-0
X-axis: Fe Thickness (cm)

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HSGM - High Sensitivity Gamma Monitor

• HSGM Detects Gamma Radiation from SF

- – Gross defect measurement
- – HSGM and CPMU
  - ➢ Both very crude measurements
  - ➢ Not very definitive
- – Can give higher measurements from empty container for damaged SF as from full container
- – Dummy element
  - ➢ Can be irradiated
  - ➢ Gives off gammas

HSGM

Spent Fuel Pool

Gamma Detector Head

Spent Fuel Assemblies
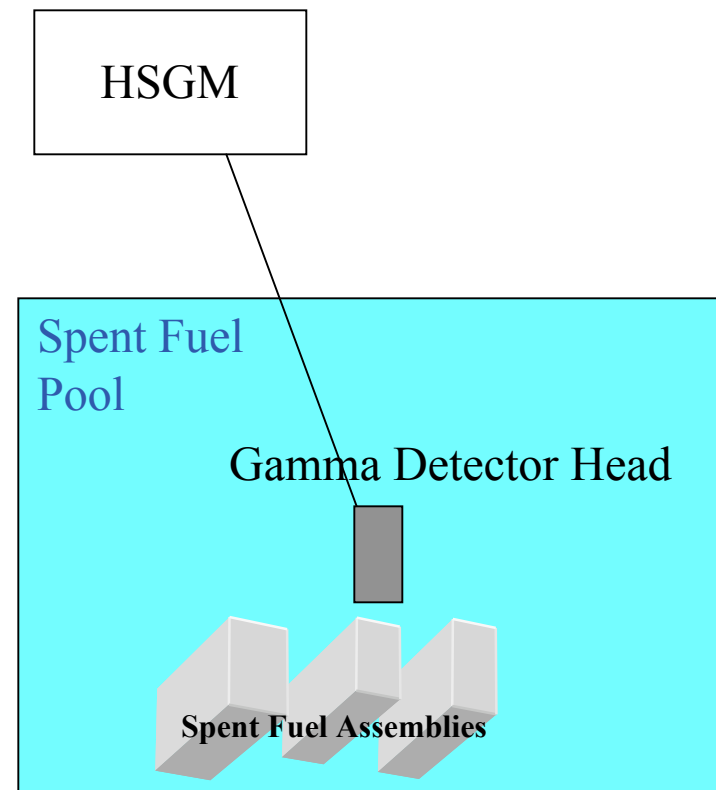
Verification of Domestic and Int'l Transfers
Spent Fuel - To Difficult-to-Access

- # Transfers of SF into containers for long-term storage under SG but difficult-to-access
  - Item I.D.
  - NDA
    - High detection probability for gross and partial defects
  - Under dual C/S

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Verification of Domestic and Int'l Transfers
Fresh LEU Fuel

- ## Fresh LEU fuel since the last PIV
  - Verified at any inspection
  - *Or* at PIV

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Material Balance Evaluation

- Evaluate non-zero SRD
  - (in LWRs normally zero)

- Evaluate non- zero MUF
  - (in LWRs normally zero)

- Evaluate on item count, I.D., and defect test results

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Confirm Absence of
Unreported Production of Plutonium

- PERFORM

  – Analysis of reactor shows it could not produce 1 SQ of unrecorded Pu per year

- OR

  – C/S on RPV to confirm RPV was closed AND
  – C/S on open RPV to confirm that 1 SQ was not removed from the core AND
  – Empty RPV - confirm CF is in SF and none removed

- AND

  – C/S acceptable on SF pool OR
  – Verify SF Pool after refueling with NDA where appropriate

Design Information Verification (DIV)

- Design info provided to Agency by the State is…
  - Examined
  - Verified

- Once a year re-examined

- Periodic verification of design information
  - To confirm continued validity
  - DIV includes
    - Taking of environmental samples….

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Typical Agency Yearly Schedule at LWR

- ## 3 interim inspections and PIV scheduled

- ## Special inspections for transfer of SF in casks
  - Verify SF as placed in cask
  - Follow with C/S to maintain CofK

- ## Pre PIV

  - Verify FF
  - Detach seals on reactor or transfer paths
  - Install temporary surveillance to reactor

- ## Post PIV
  - Attach seals on transfer paths (canal gate, etc,)

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IAEA Containment Sealing Systems

- IAEA Metal Seal

- COBRA Seal (In-Situ verification)

- VACOSS Seal (Electronic Seal with fiber optic wire - can be opened and closed ONCE by operator)

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LWR – Containment/Sealing

- Surveillance Instruments (Cameras, Surveillance Cabinets)

- Reactor Hall
  - Vessel Missile Shield (VVER 440)
  - Other means to immobilize Core Fuel

- SF Pool
  - Spent Fuel Racks and Pool Covers
    - Immobilization of SF
  - Loaded SF casks ready for shipment to
    - Interim Storage
    - Dry Storage
    - Off-site
  - Re-fueling crane - temporary measure to avoid losing CofK

- Exit pathways
  - SF Pool canal gate and Exit hatches

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Operator/Inspector Measurement System - Definitions

Total (relative) measurement uncertainty

$$\delta_i = (\delta_O{}^2 + \delta_I{}^2)^{1/2}$$

METHOD CODES	INTERPRETATION	RELATIVE ERROR RANGES	DETECTABLE DEFECT SIZE
H	Quantitative through NDA (Verification in the attribute mode using the least accurate method), or	$0.0625 < \delta_i \le 0.125$	GROSS
	Qualitative through NDA (e.g. Cerenkov, bundle counter)	Error can not be assigned	GROSS
F	Quantitative through NDA (Verification in the attribute mode using a better accurate method)	$0.010 < \delta_i \le 0.0625$	PARTIAL
E	Quantitative through NDA (Verification in the variables mode using the most accurate method) e.g. K-edge densitometer	$\delta_i \le 0.01$	BIAS
D	Quantitative through DA (Verification in the variables mode using the most accurate method)	$\delta_i \le 0.01$	BIAS

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LWRs and RRCAs

- Research Reactors with 25MWth output have concerns with
  – Unreported Pu Production

- Use of reactor power monitor to observe power output for RRCA
  – Estimate Pu production
  – Thermal-hydraulic and radiation power monitors

- Reactor power monitor - not used in LWRs
  – Intrusive nature
  – Operator supplies thermal output info
  – Possible satellite photo analysis – expensive mode

- Need for tool to give power output information
  – Operational information
  – Possible Pu Production calculations

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LWR Safeguards Goal and Issues

- Control of Spent Fuel - source of PU

- Control of SF pool items - targets for Pu production

- Control of LEU fuel -
  - Source of LEU for enrichment
  - Pu production in reactor
    - Understanding of power history of reactor
      - Possible role of Antineutrino Detector

- Control of MOX fuel - source of unirradiated Pu

- Control of transfers - SF that may be reprocessed for Pu

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LWR Safeguards Needs

- SF Pool
  - Ability to insure no tampering with SF assembly
  - Assembly removal/substitution by dummy
  - Pin Diversion/substitution by dummy

- Thermal Power of LWRs
  - Verify operator's declaration
    - ➤ Possible role of Antineutrino Detector

- SF assembly inventory (of interest for reprocessing)
  - Operator's calculations
  - Verify operator's declaration at reprocessing plant
  - Develop independent means to verify SF

- Undeclared activities - Possible role of Antineutrino Detector

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